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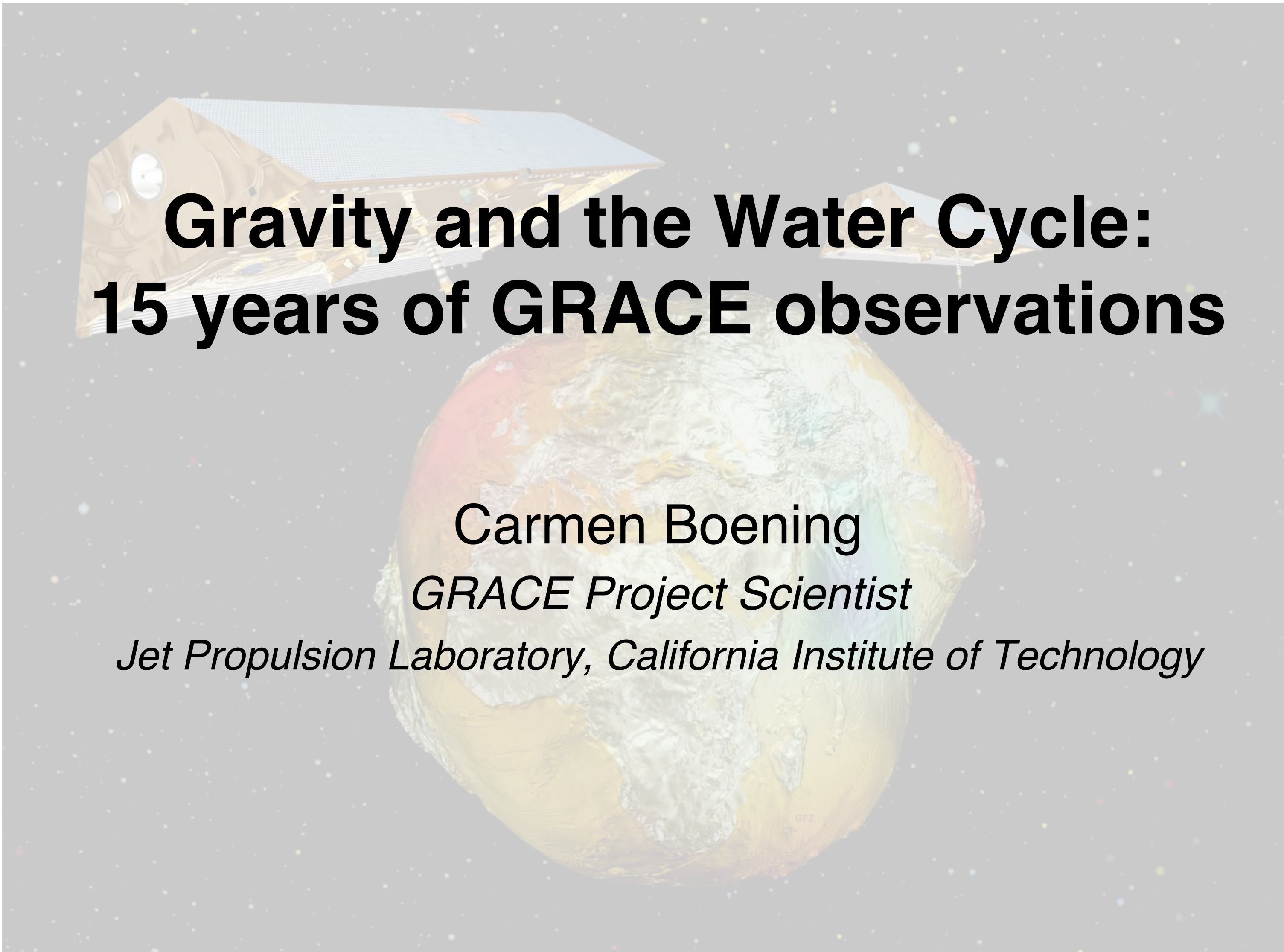
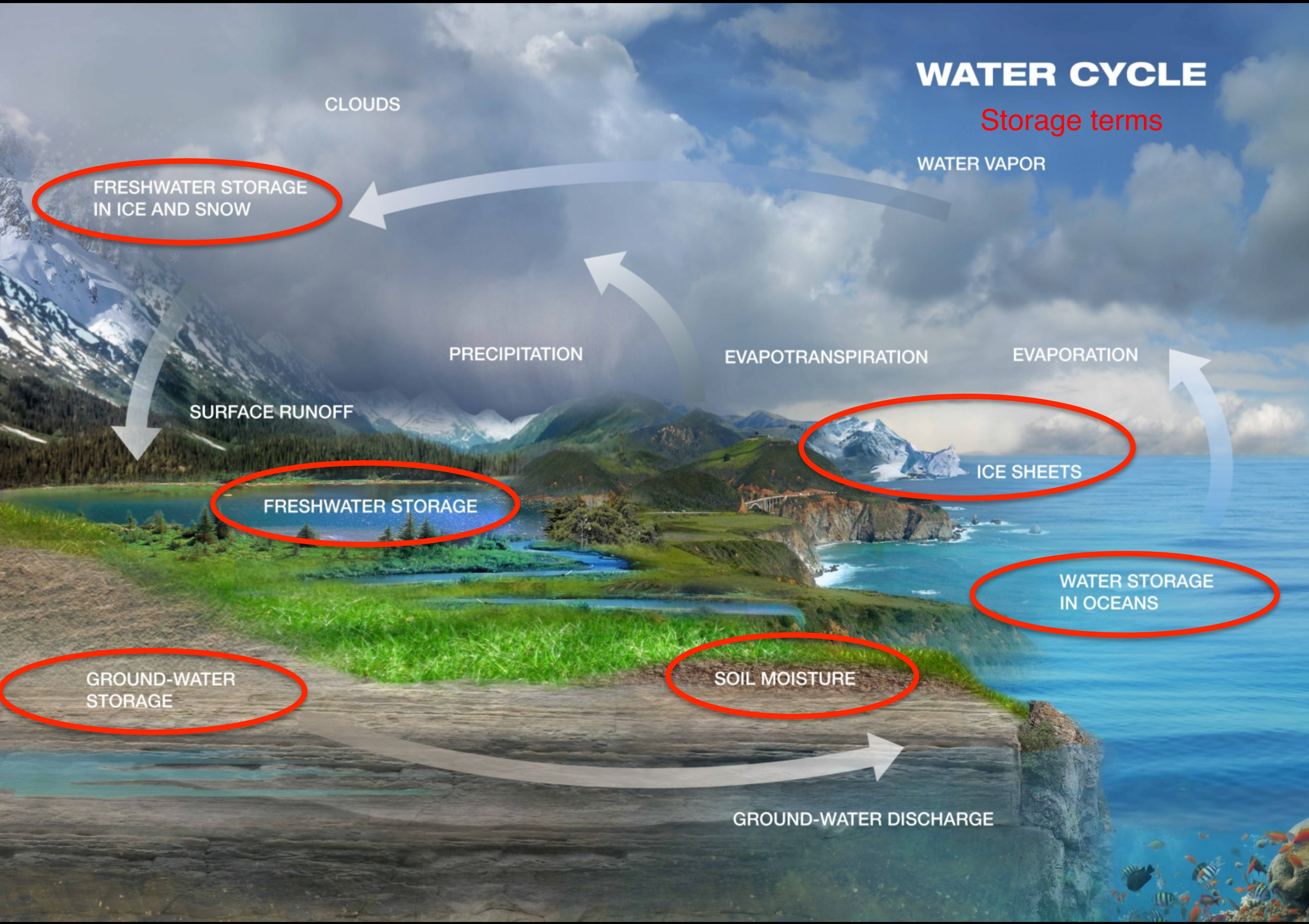


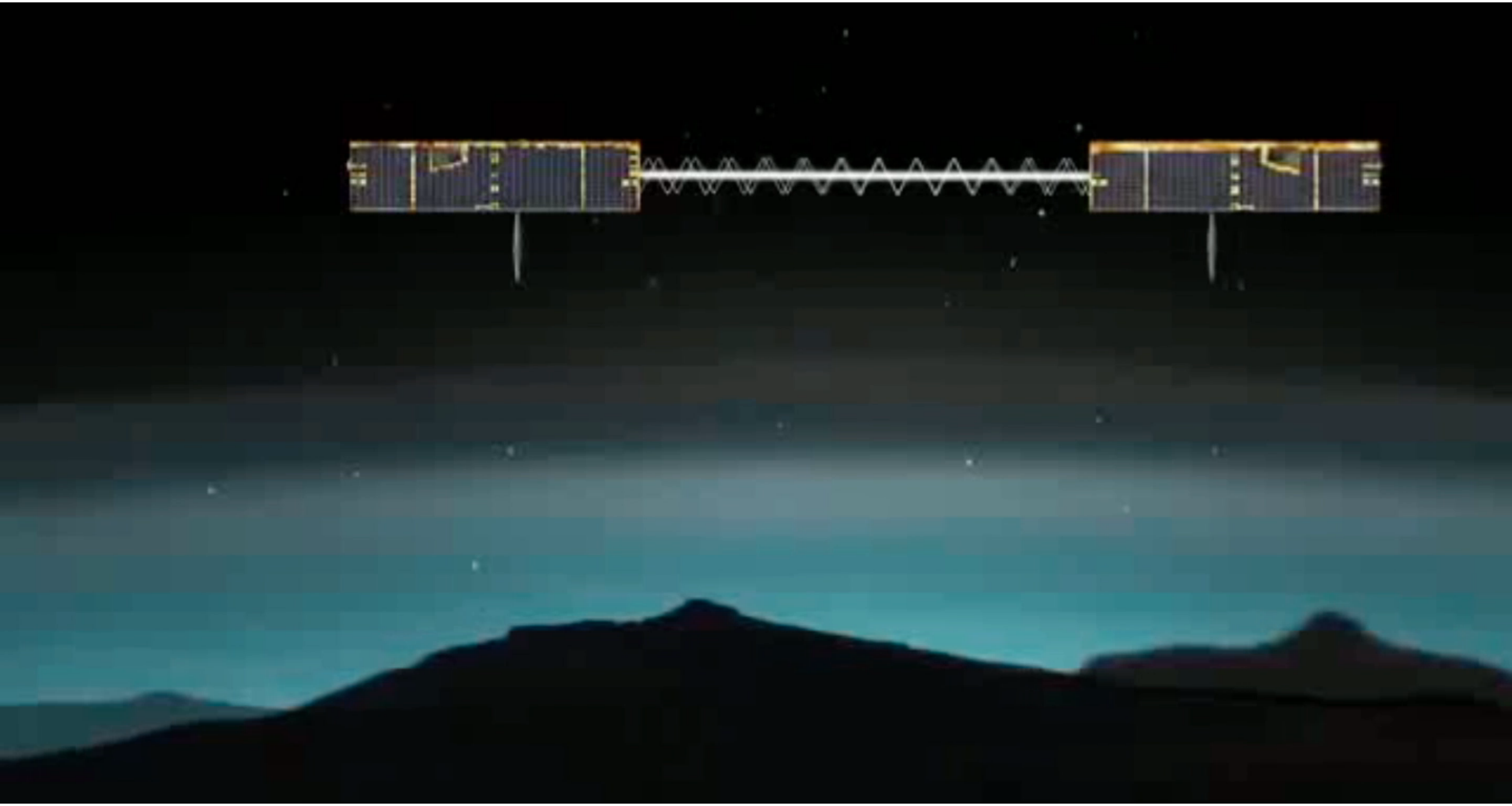
Gravity and the Water Cycle: 15 years of GRACE observations

Carmen Boening
GRACE Project Scientist
Jet Propulsion Laboratory, California Institute of Technology

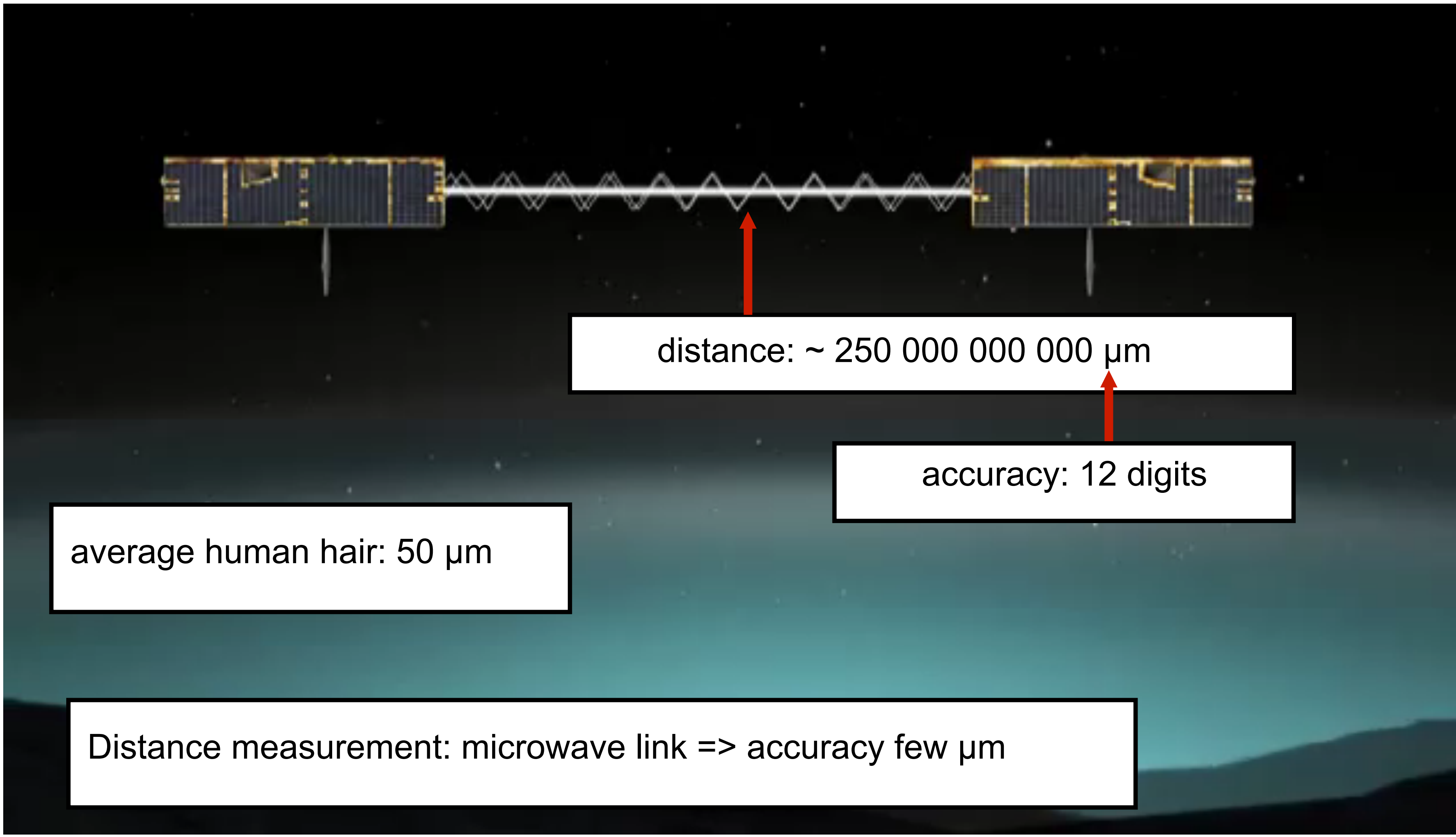

WATER CYCLE
Storage terms
CLOUDS
WATER VAPOR
FRESHWATER STORAGE
IN ICE AND SNOW
PRECIPITATION
EVAPOTRANSPIRATION
EVAPORATION
SURFACE RUNOFF
ICE SHEETS
FRESHWATER STORAGE
WATER STORAGE
IN OCEANS
GROUND-WATER
STORAGE
SOIL MOISTURE
GROUND-WATER DISCHARGE

Gravity Recovery and Climate Experiment

GRACE Measurement



GRACE Measurement



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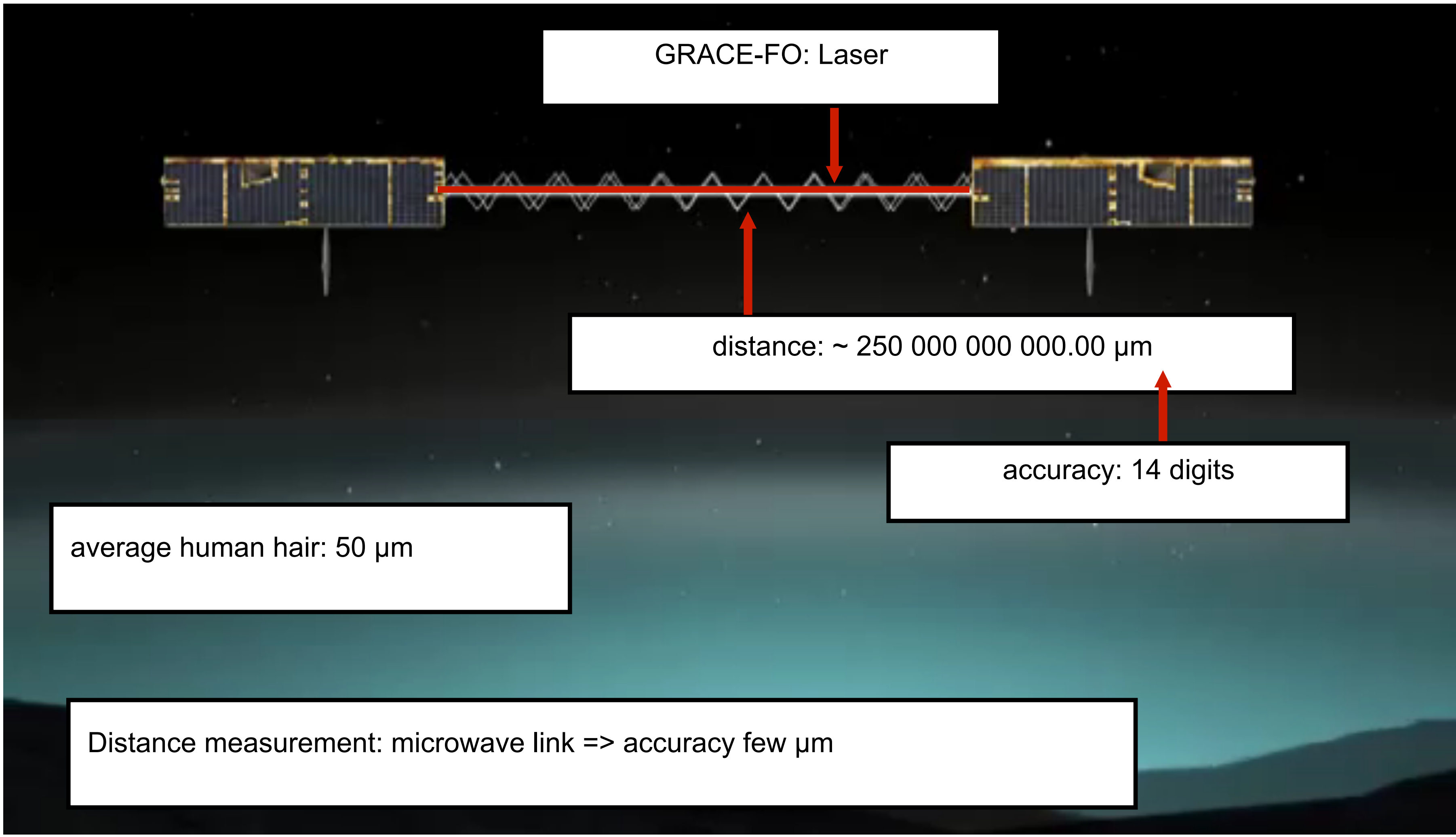
GRACE & GRACE-FO



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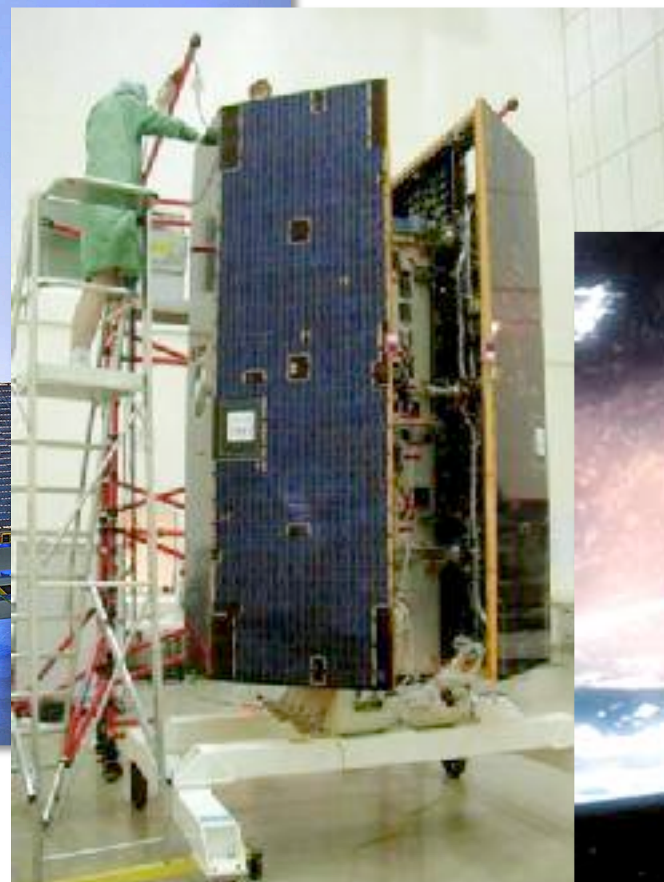
GRACE Satellites in 2002



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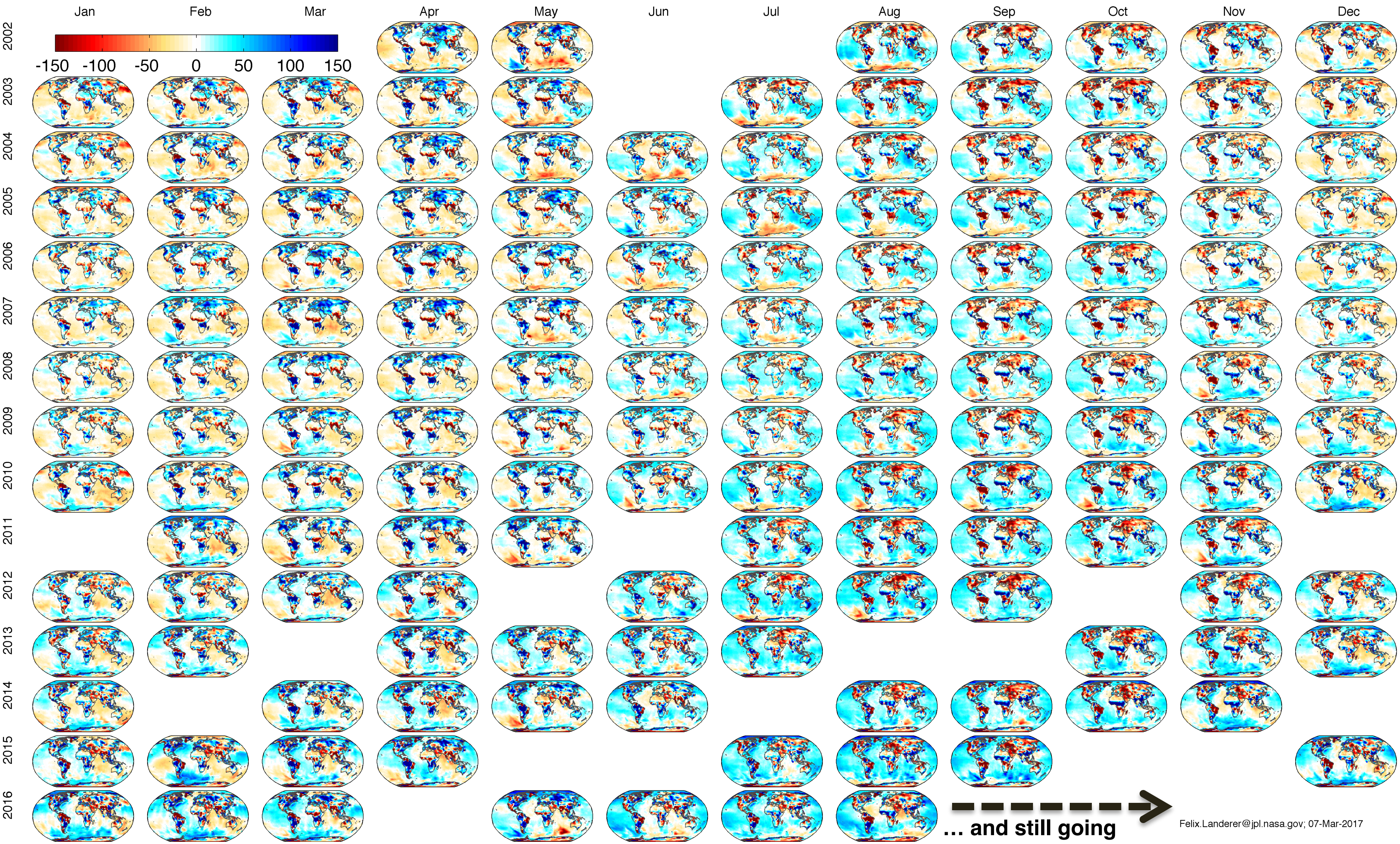
March-2016: Happy (15th) Birthday!

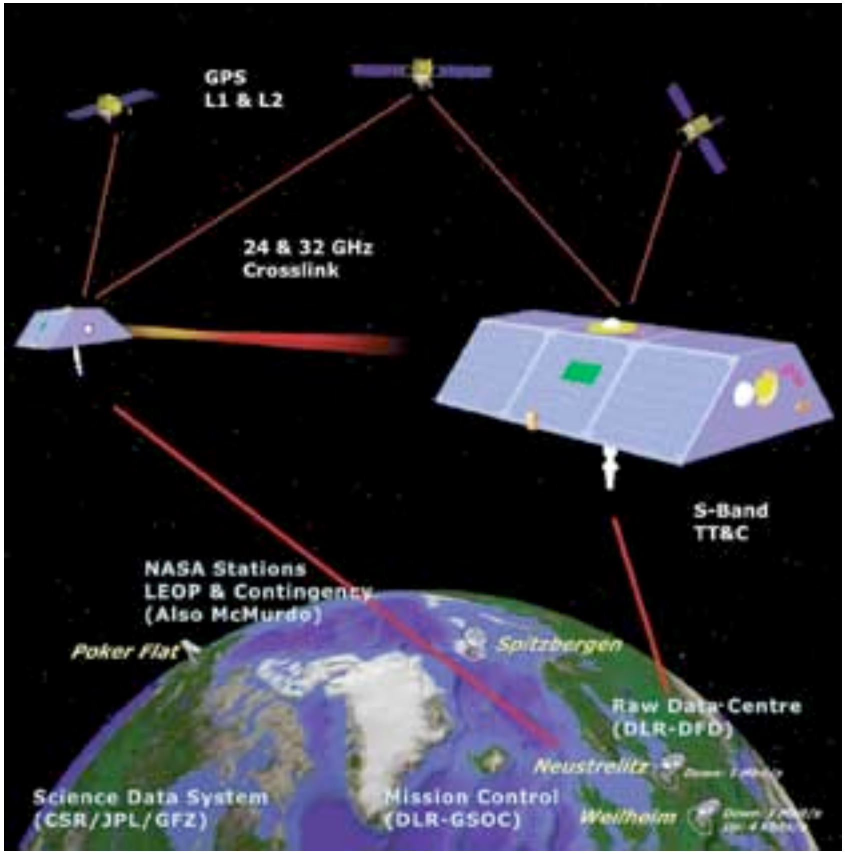


Carmen Boening – Gravity and the Water Cycle: 15 years of GRACE observations

Mission Status

Launched: March 17, 2002
Nominal mission: 5 years
14.99 years in orbit (5472 days)
Initial altitude: 485 km
Current altitude: ~336.4 km (-88 m/d)
Operations Challenge: Operate until 2018
2015 NASA Senior Review identified an overlap with GRACE-FO mission as a high priority objective

Mission Lifetime Issues
Altitude Decay: Drag estimates predict lifetime to last at least through 2017
Battery Capacity: Uncertain, but current strategy *might* allow operation until 2018.
Propellant for Attitude Control: Available until end of 2017
Single String Instrument Operations:
Degraded science mission options under study



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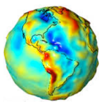
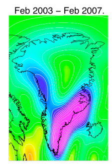
A history of discoveries

Static field



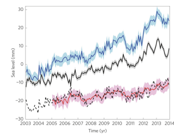
Launch

First trends



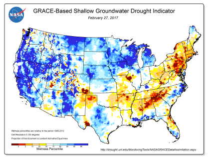
Ice melt

Interannual variability



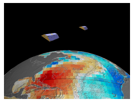
Sea level budget

Low latency



Water resources

Improved products



Deep ocean circulation

Prime Mission

Extended Mission

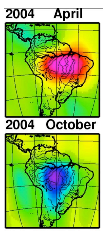
2002

2007

2012

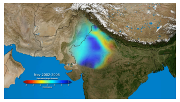
2017

Seasonal



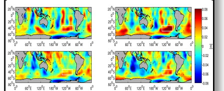
Hydrology

Water column observation



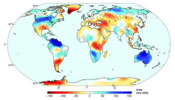
Groundwater extraction

Small signals



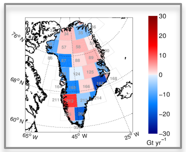
Wind-driven Oceans

Interdisciplinary research



Water cycle

Improved products



Regional change

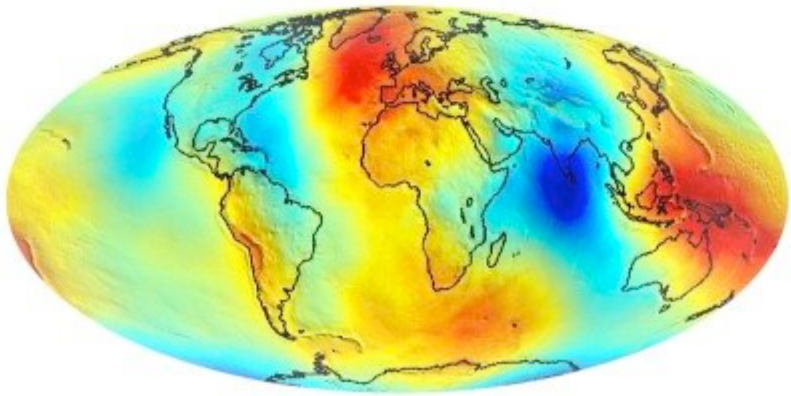
Large Scale → Small scale

Global → Regional

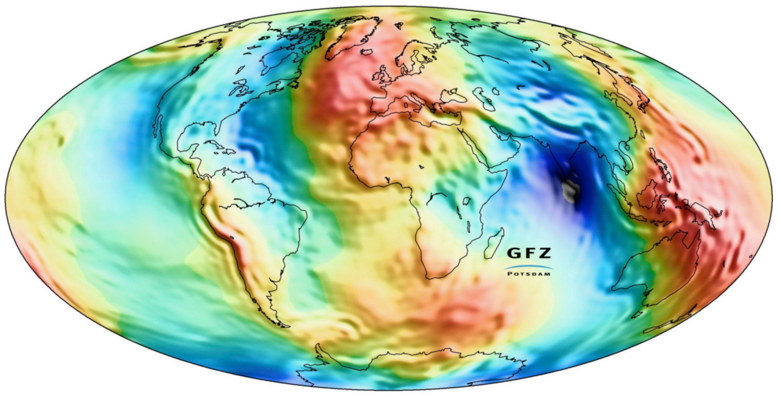
Static field and seasonal → Interannual/decadal and operational

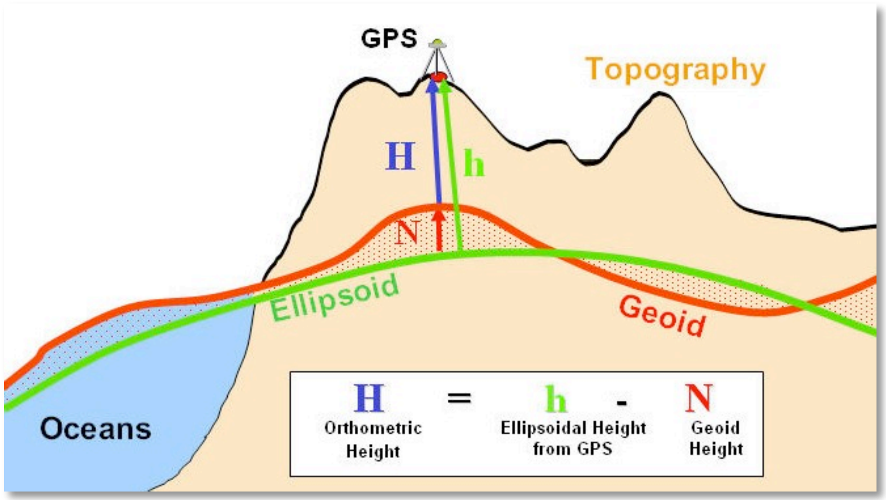
Geoid – The Static Gravity Field

Then …



… Now



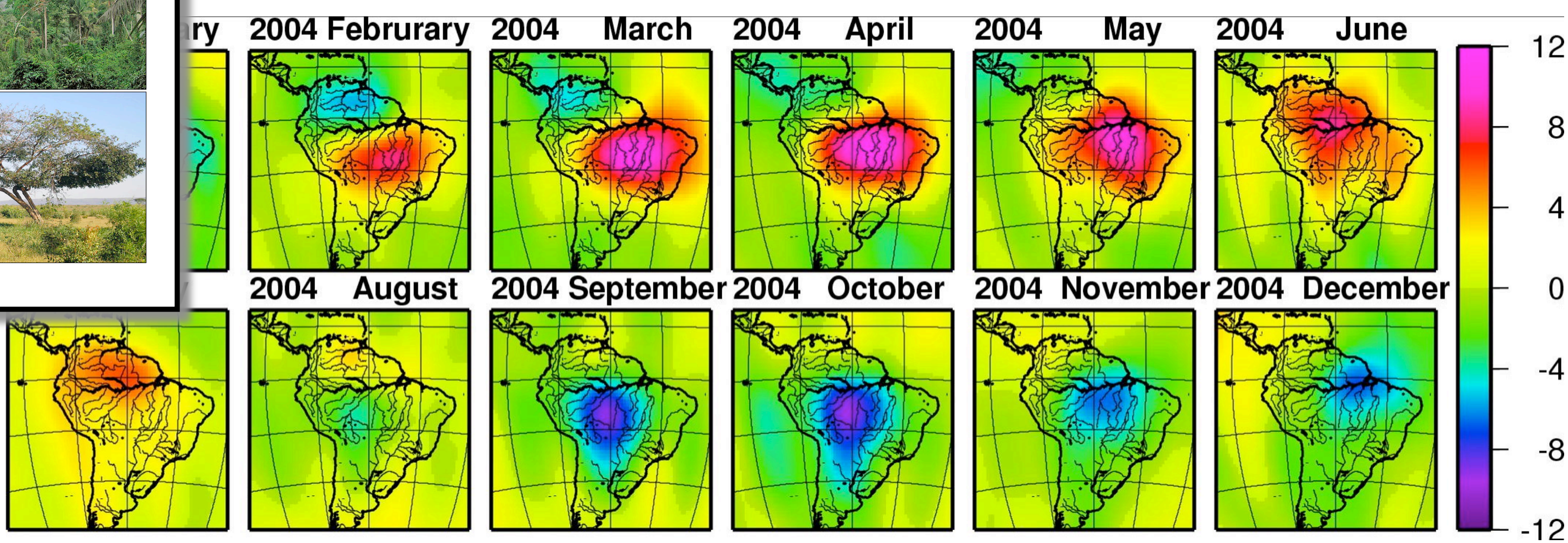


Geoid important reference surface, particularly for ocean applications

Two orders of magnitude improvement compared to pre-GRACE

Observing seasonal variability in land hydrology

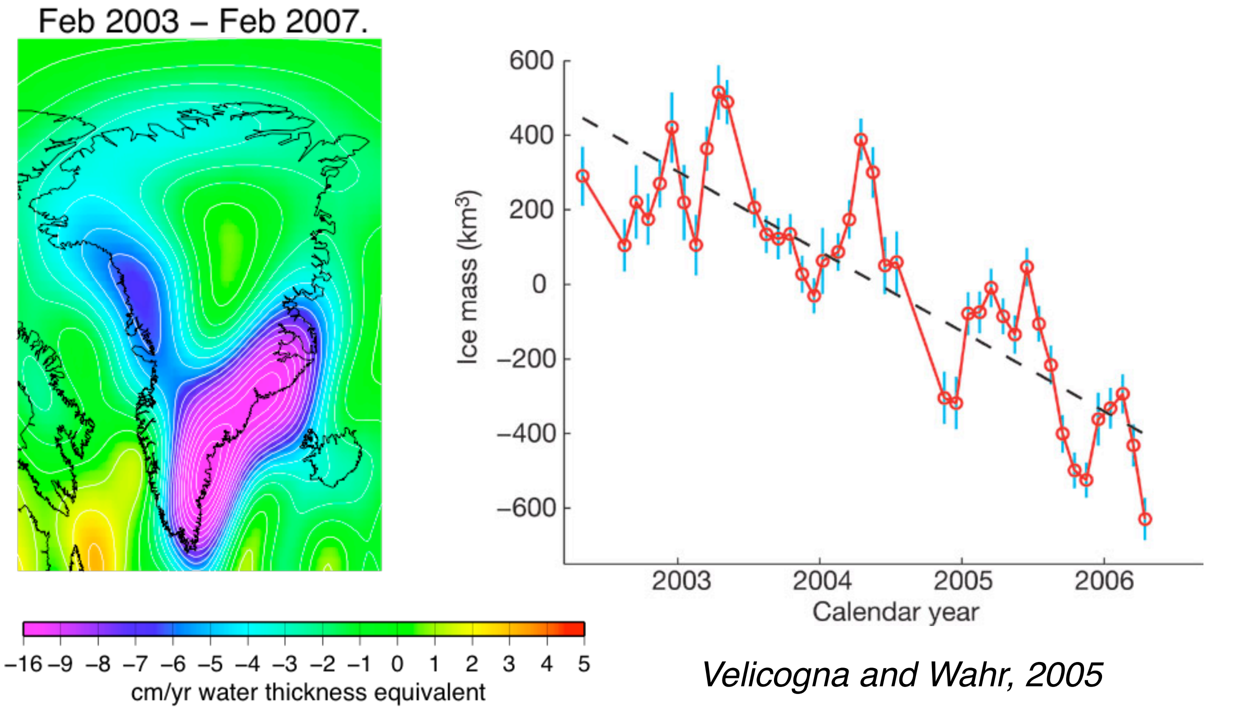
Hydrologic variability



GRACE helps to characterize the rainy and dry season over major hydrologic basins

Chen et al., 2005

First big signals in the time-varying gravity field: Greenland mass loss



Velicogna and Wahr, 2005

GRACE allows for a first look at Greenland ice loss

- First quantitative measurement
- Characterization of seasonal cycle

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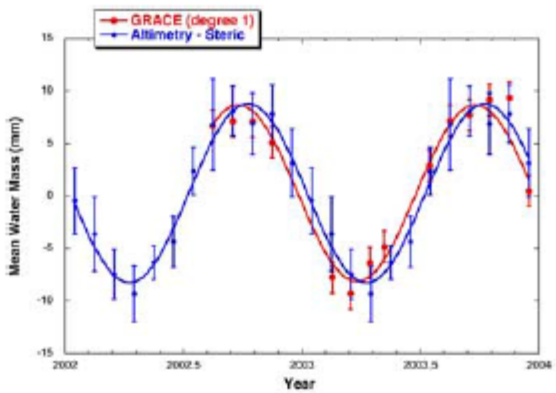
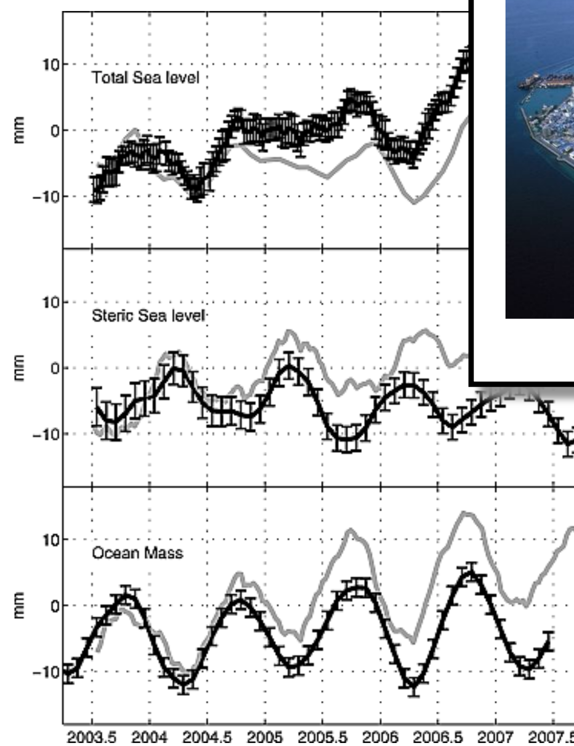
Jet Propulsion Laboratory
California Institute of Technology

From big signals over land to small signals over the ocean

From seasonal to interannual: Sea level budget on different time scales



Chambers and Wahr, 2005

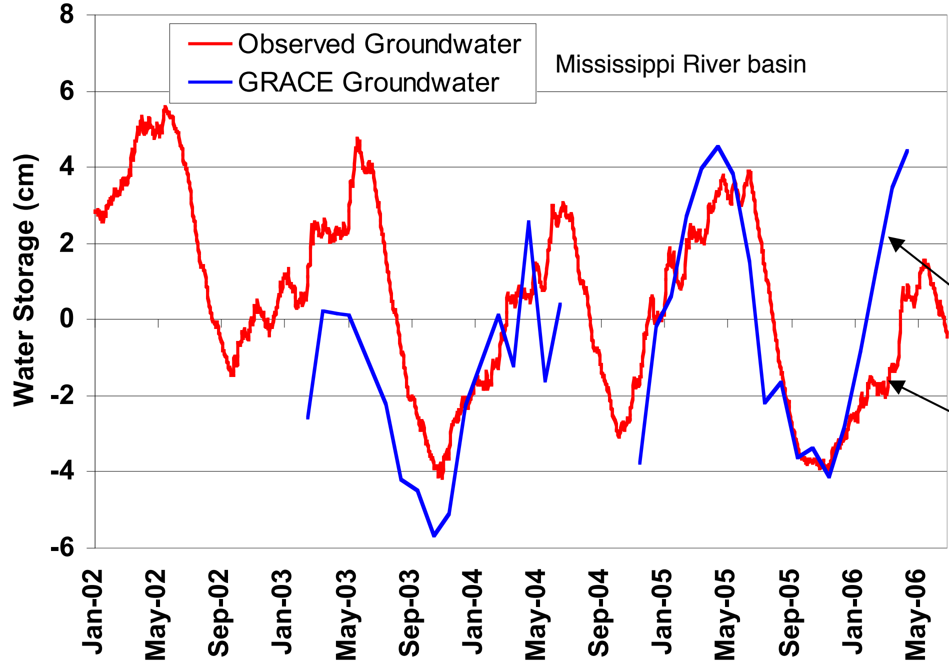


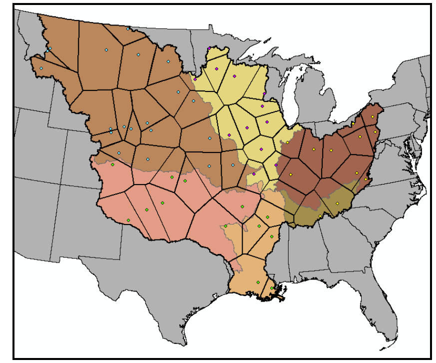
Willis and Chambers, 2008

Sea level

First combinations with complementary satellite and in-situ data

GRACE Is the First Satellite to Monitor Groundwater Levels

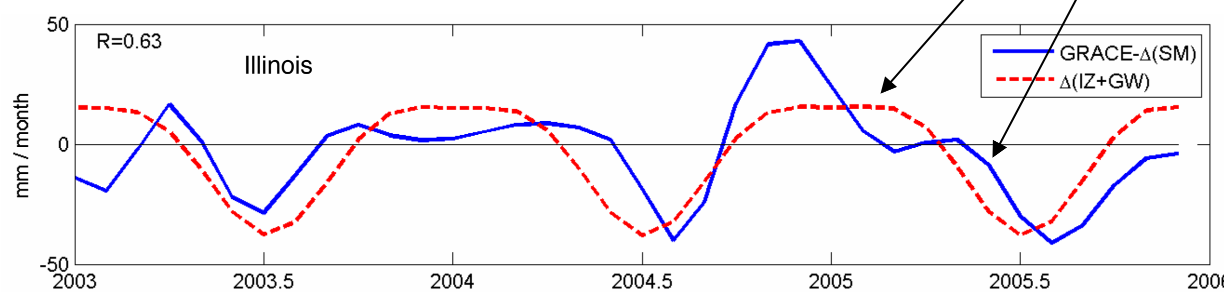




GRACE groundwater estimate

Groundwater well observations

GRACE groundwater estimates (smoothed)



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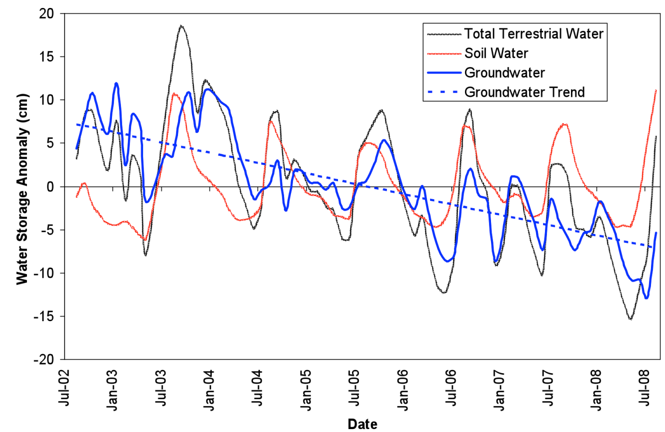
GRACE: Tracking Earth’s Groundwater

Groundwater depletion in NW India

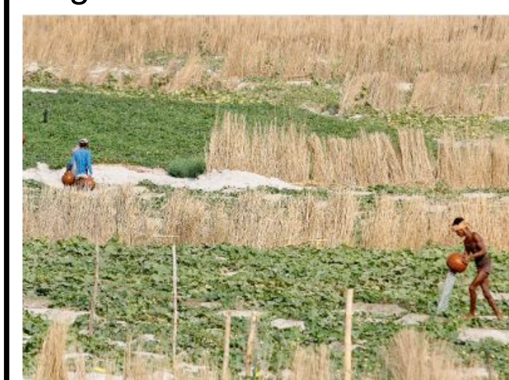


Rodell et al., 2009

GRACE reveals groundwater depletion due to irrigation

Water storage changes not visible at the surface but visible in gravity

Irrigation



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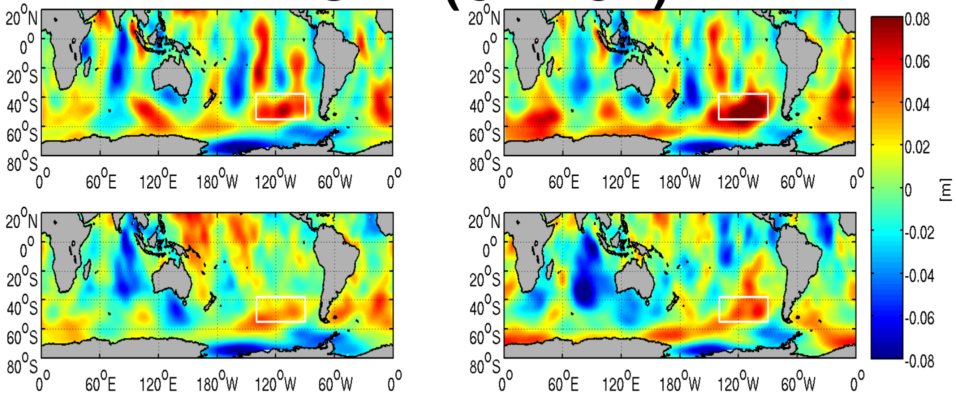
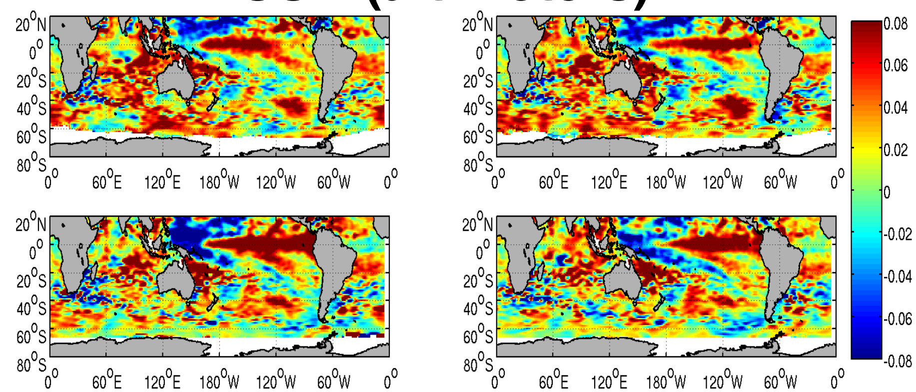
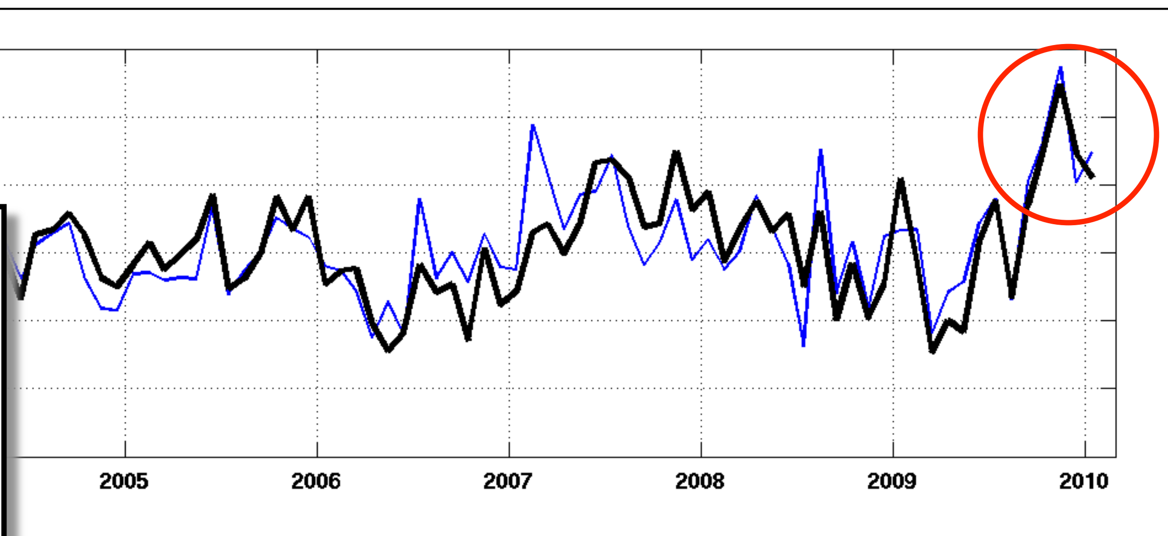
From big signals to small – GRACE for understanding ocean circulation

OBP (GRACE)



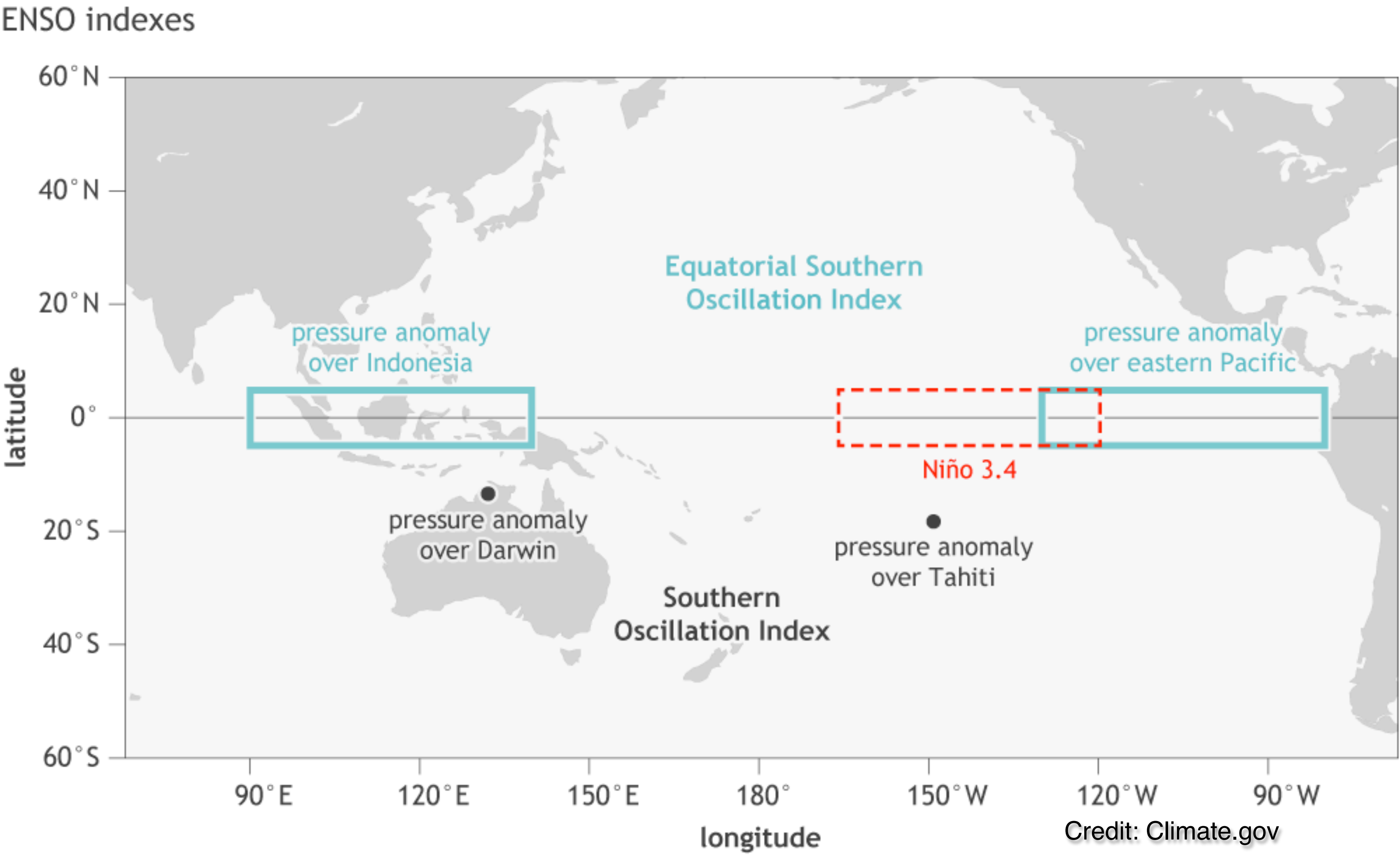
SSH (altimeters)





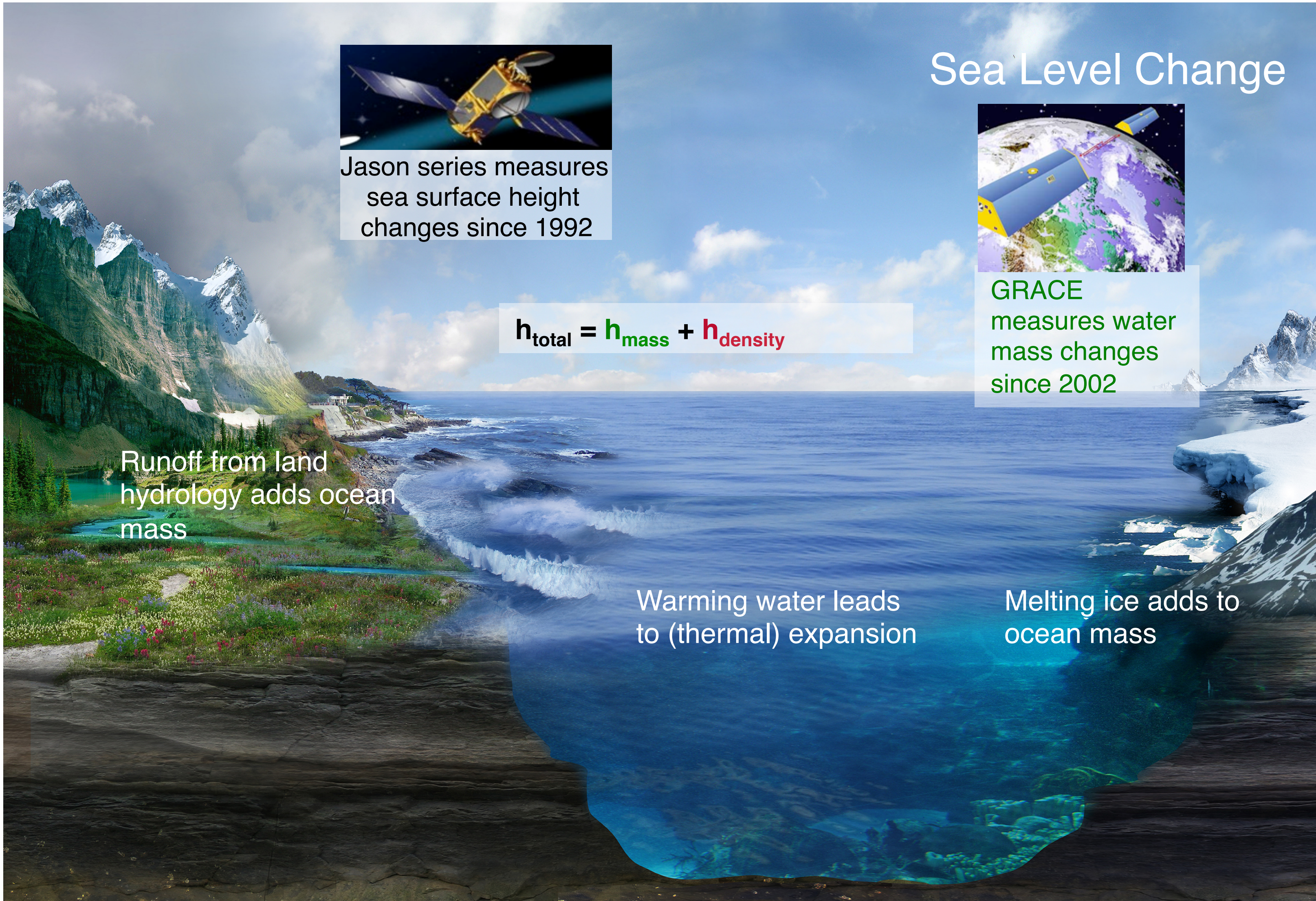
Ocean circulation

Long-term vs. short-term variability – ENSO and the water cycle



Credit: Climate.gov

Causes and Observations of Sea Level Change



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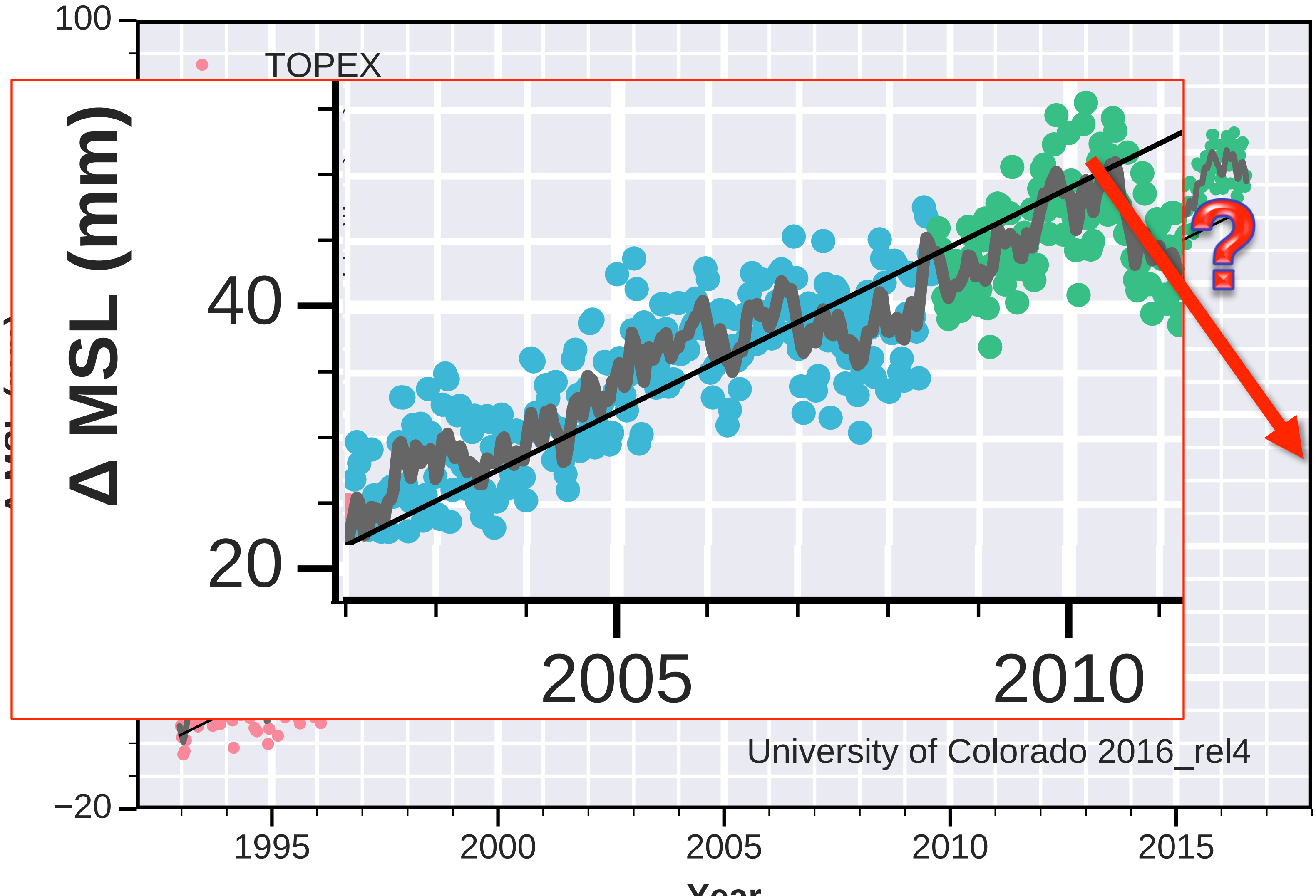
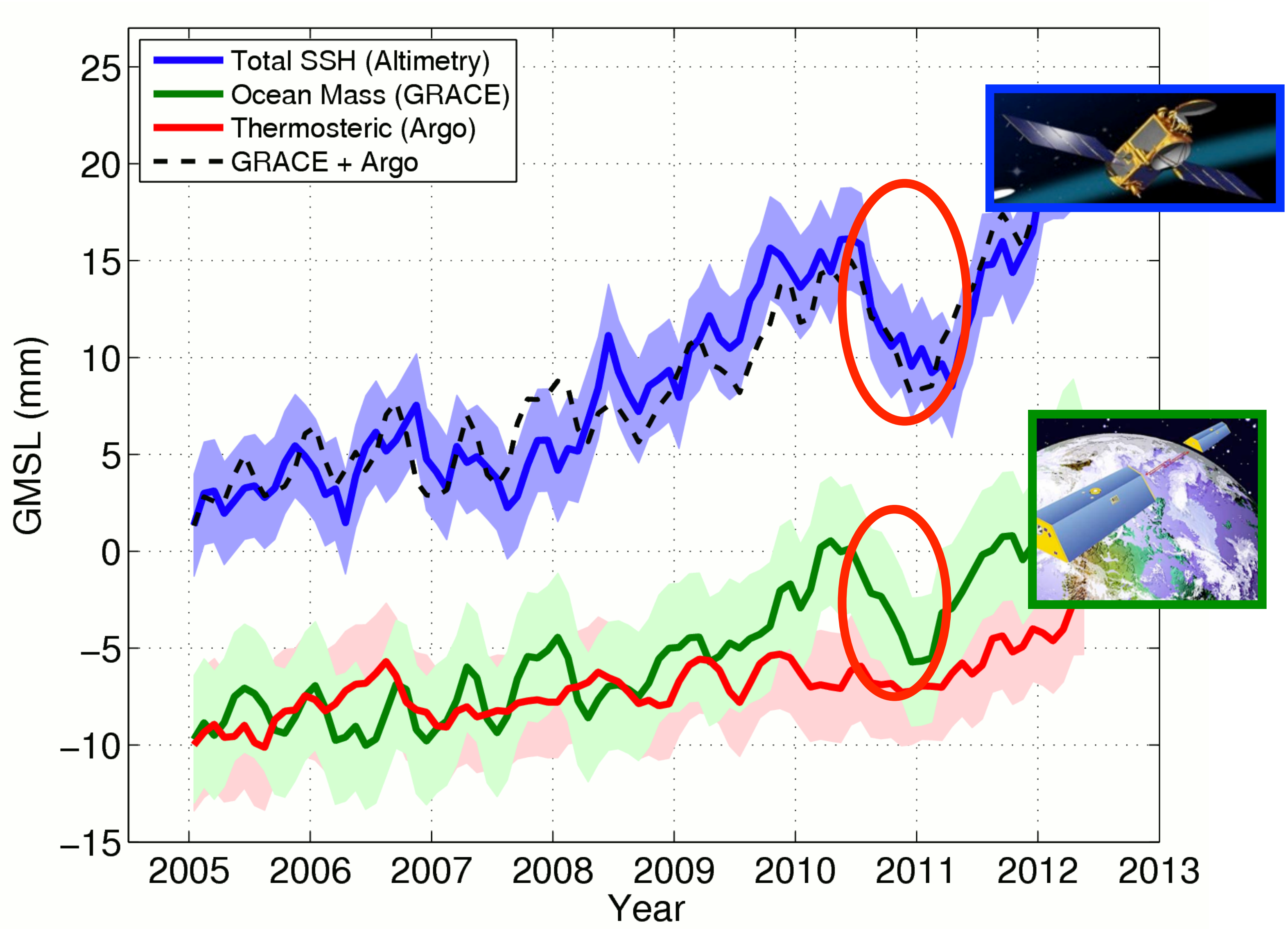
Records of sea level change since 1992



Using Multiple Satellites to “Track” Water



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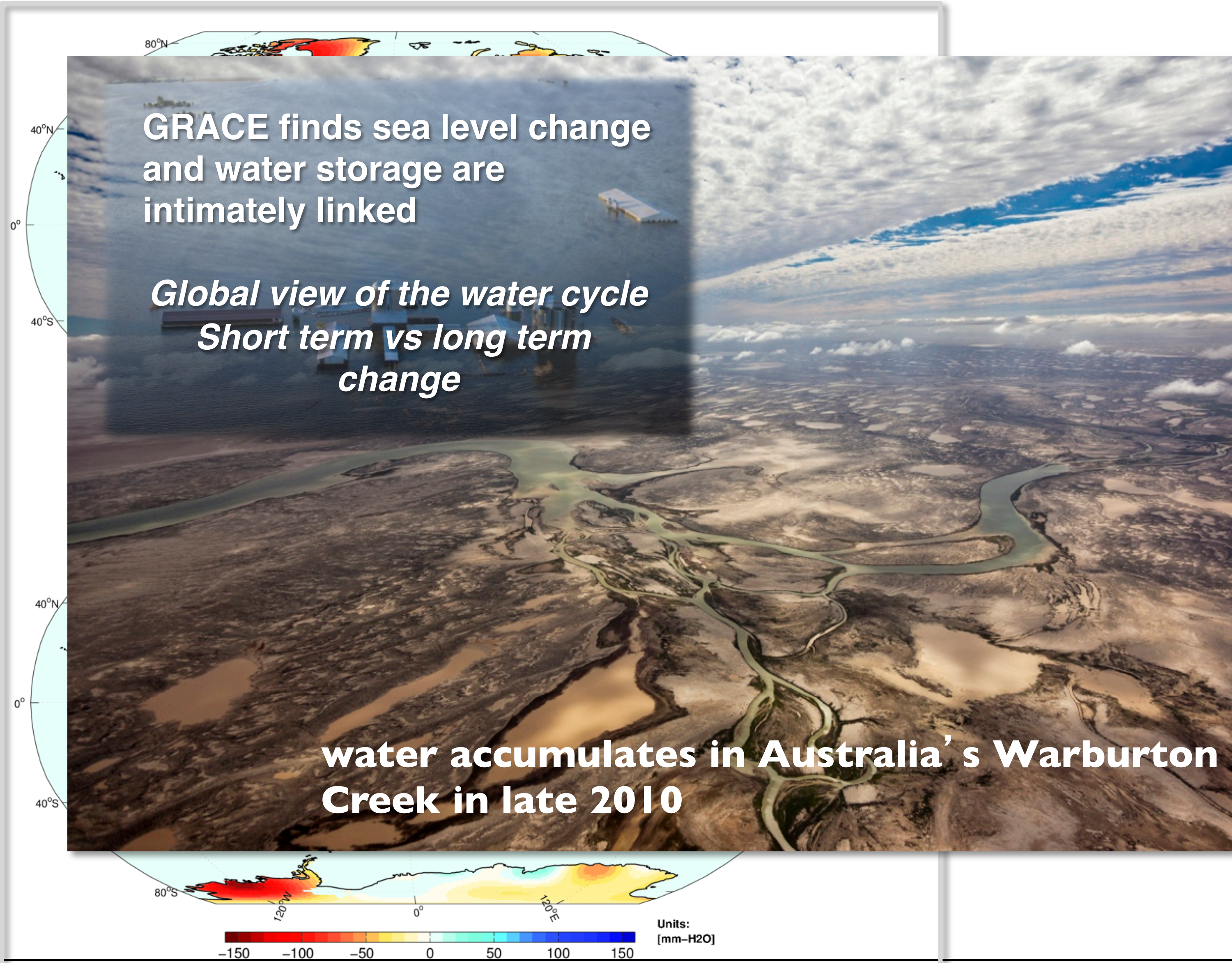
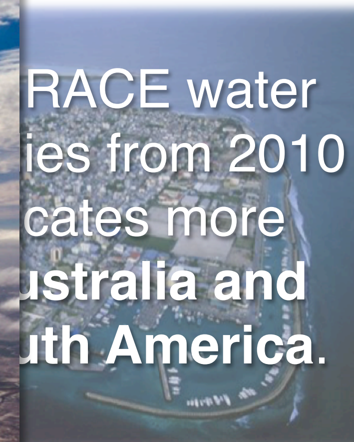
Terrestrial Water Storage in 2010 and 2011



Mass in millimeter of water thickness



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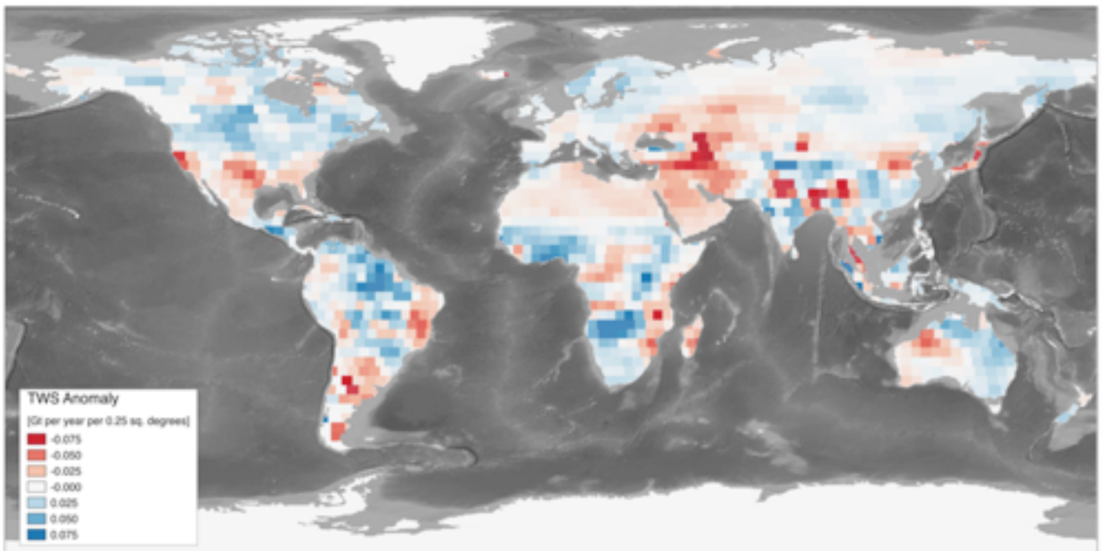
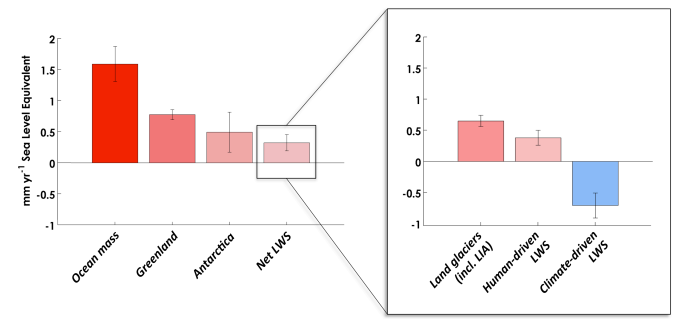
Sea Level Rise Slowed by Climate-Driven Hydrology



Reager et al., 2016

Sea level and hydrology



Importance of decadal change in hydrology:

GRACE helps to re-assess sea level trends

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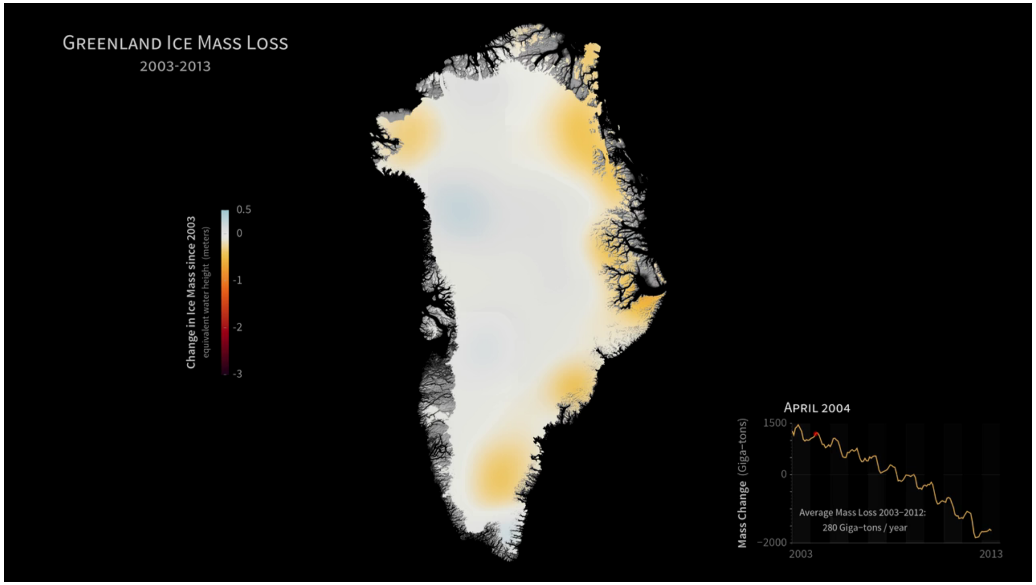
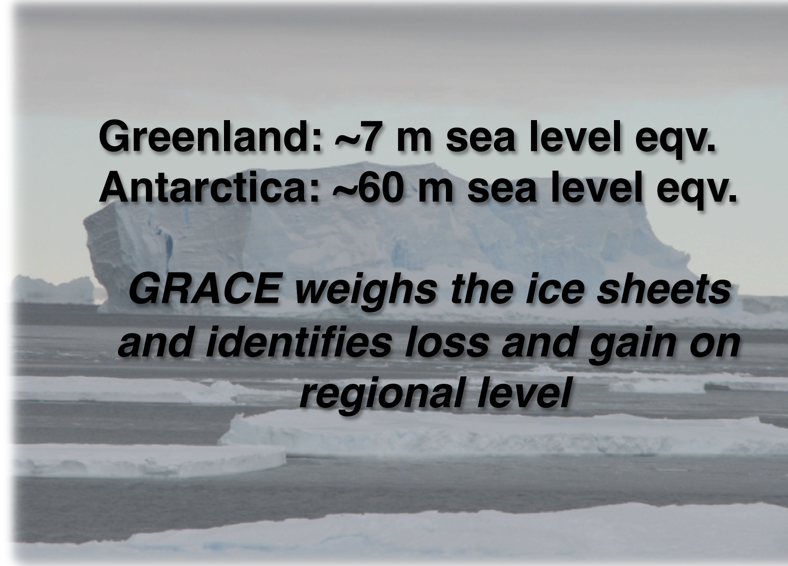
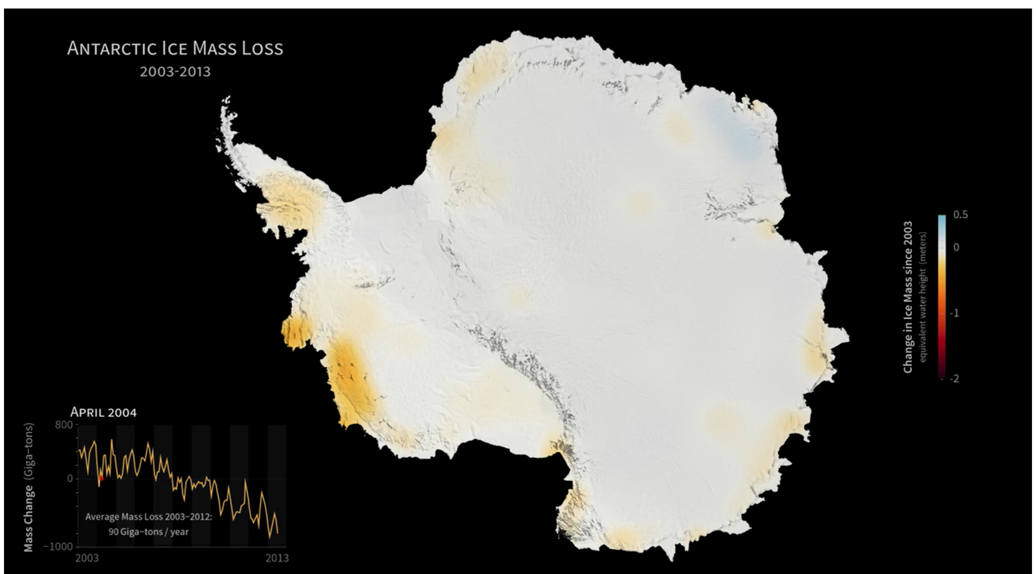
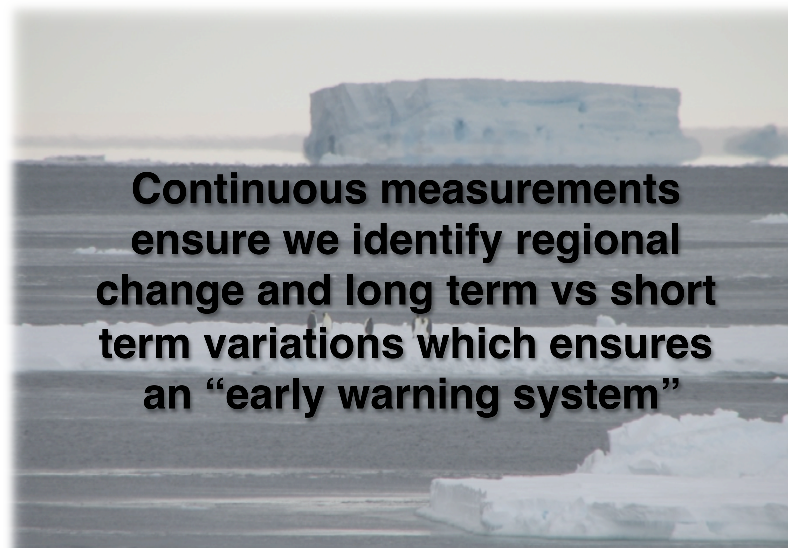
Ice Sheet Loss affecting sea level









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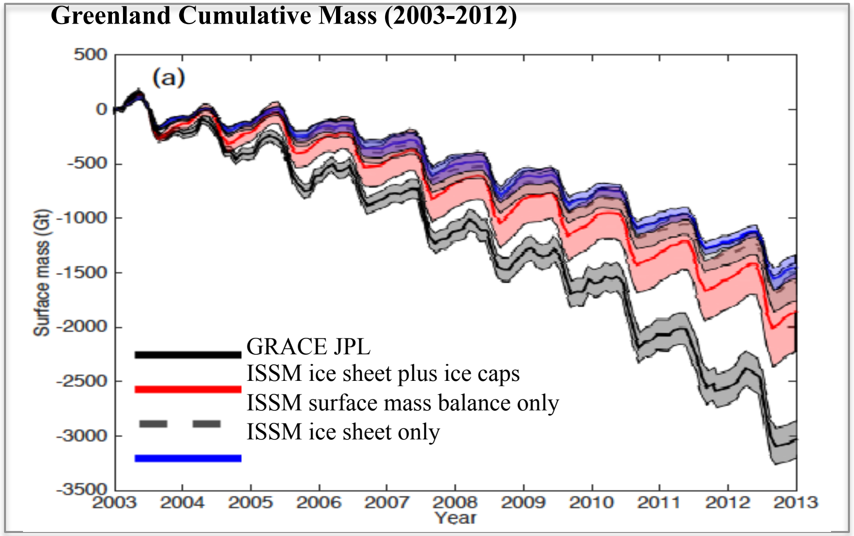
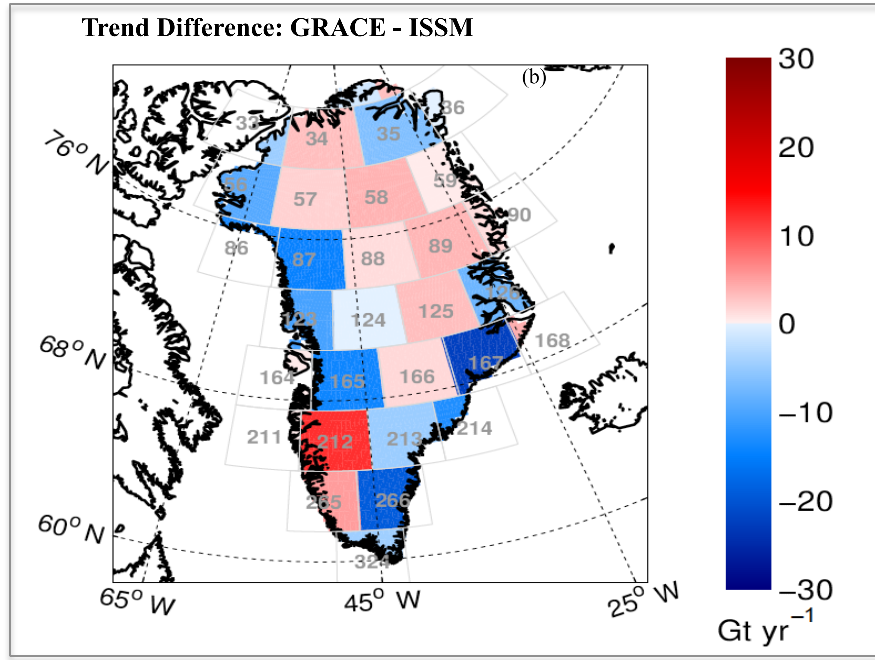
Utility of GRACE in assessing model estimates of Greenland mass change



Schlegel et al., 2016



Identifying processes behind ice mass loss by combining GRACE data with ISSM model output - Surface mass balance vs. discharge

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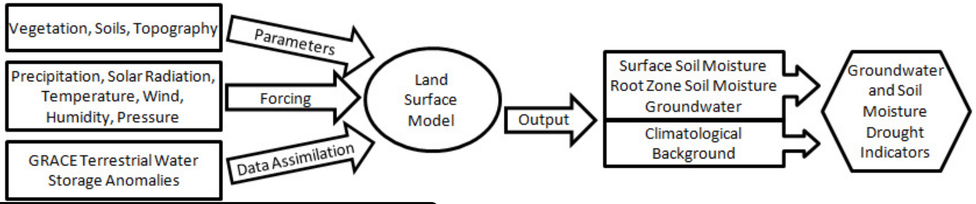
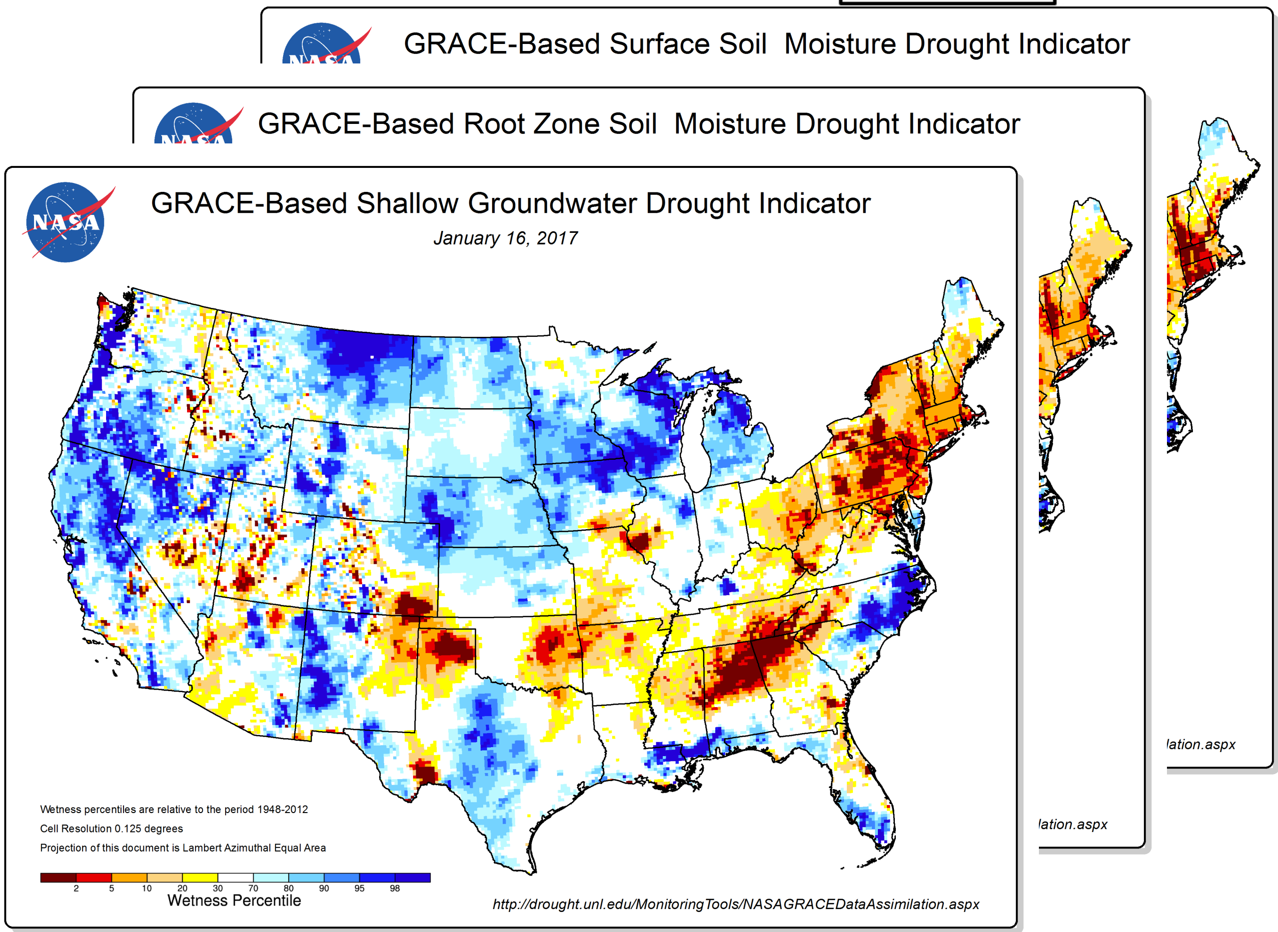
GRACE for operational use: National Drought Monitor





Weekly GRACE data assimilation for Soil Moisture and Groundwater Drought Indicators

Integral water storage provides insights into below-surface water reservoirs

California drought

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

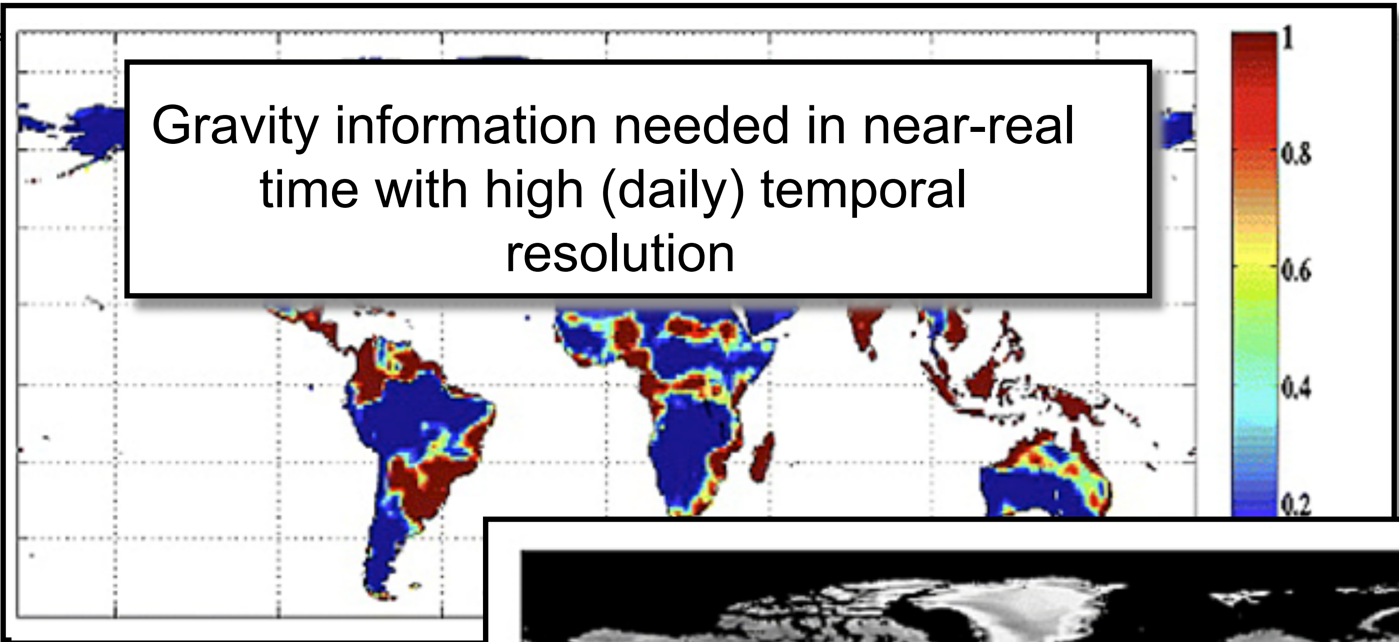
Gravity for early warning?

Saturated soils

Danger of flooding

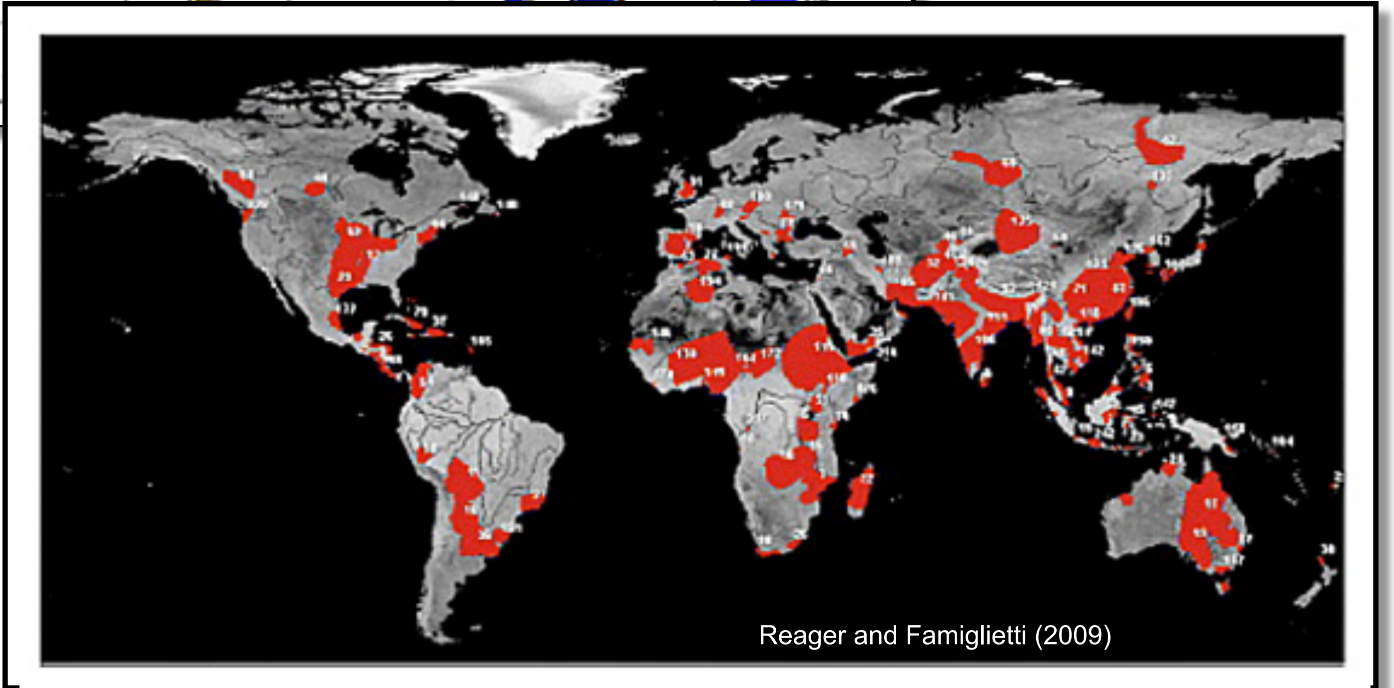
Flood indices for early warning before flood actually occurs

Gravity for early warning?



Gravity information needed in near-real time with high (daily) temporal resolution

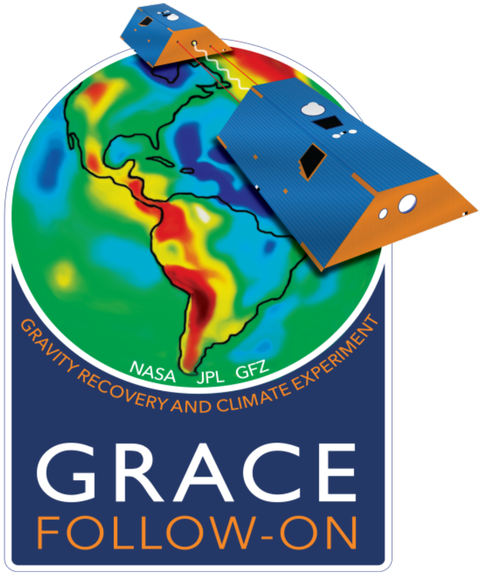
GRACE-derived flood index (May 2007)



Floods that actually happened May 2007

GRACE Follow-on Project Overview

GRACE Follow-On

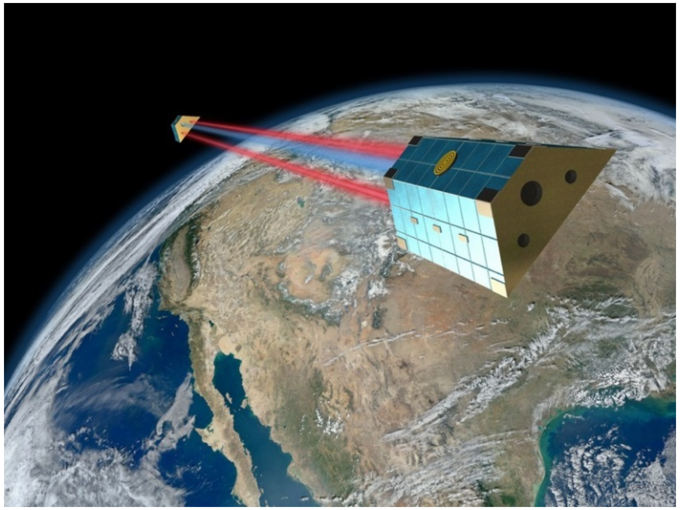


Salient Features

- *Implemented under US-German partnership*
- *Tech-Demo Laser Ranging Interferometer is Class D*
- *Follow-on to original GRACE Mission launched 2002*
- *Launch: **December 2017 on SpaceX Falcon 9***
- *Orbit: Near-circular Polar Orbit, 495 km altitude, 89° inclination*

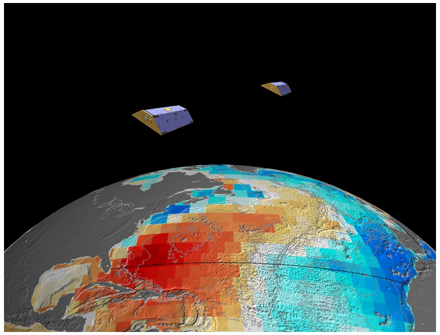
Science

- *The GRACE-FO Mission will **continue and expand** upon the measurements initiated by the pathfinder GRACE Mission*
- *Will provide estimates of the **global high-resolution models of the Earth's gravity field for a period of up to five years** at a precision and temporal sampling equivalent to that achieved with GRACE.*
- *Will provide **QuickLook products for enhanced operational use** for water resource management*
- *The inter-satellite laser ranging interferometer will demonstrate satellite-to-satellite interferometry in low Earth orbit.*

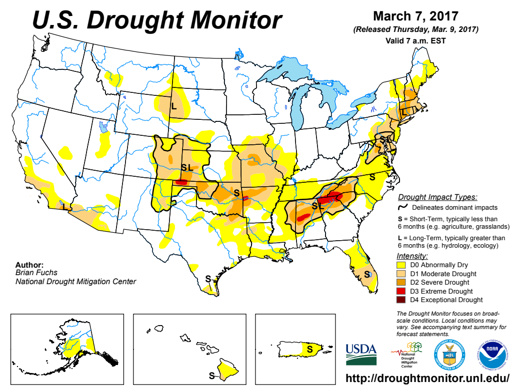


Examples for additional future research and applications

Deep ocean circulation

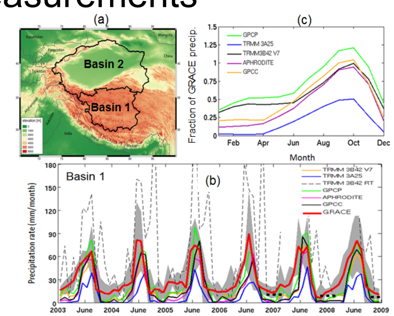


Expanding drought monitoring

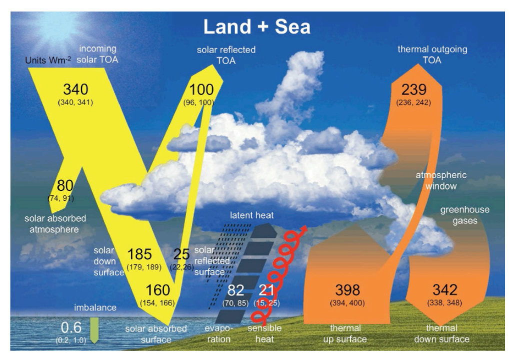


And more to come …

Constraining precipitation measurements



Energy balance and ocean heat budget



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